

# TeV gamma rays from blazars beyond $z=1$ ?

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## Abstract

At very high energies (VHE), the gamma-ray horizon of the universe is limited to redshifts  $z \ll 1$ , and, therefore, any observation of TeV radiation from a source located beyond  $z = 1$  would require a dramatic revision of the standard scenarios of propagation of VHE photons through intergalactic radiation and magnetic fields. This appears to be the case for the TeV blazar PKS 0447-439, for which a redshift  $z > 1.246$  was recently reported. In this paper we argue that the reported large redshift can be compatible with gamma-ray emission extending to TeV energies, without invoking exotic new physics, if one assumes that the observed gamma rays are secondary photons produced in interactions of high-energy protons originating from the blazar jet and propagating over the cosmological distances almost rectilinearly. This hypothesis was initially proposed as a possible explanation for the TeV gamma rays observed from blazars with relatively large, yet modest redshifts,  $z \sim 0.2$ , for which other explanations were possible. In the case of PKS 0447-439, it provides the only viable interpretation of the VHE signal consistent with conventional physics. If the observability of TeV gamma rays from blazars at  $z \geq 1$  is confirmed by future observations, our interpretation will have far-reaching ramifications for gamma-ray astronomy. Furthermore, this interpretation implies that intergalactic magnetic fields (IGMFs) along the line of sight are very weak, in the range  $10^{-17} \text{ G} < B < 10^{-15} \text{ G}$ , and that acceleration of  $E \geq 10^{17} \text{ eV}$  protons in the AGN jets is indeed very efficient.

The recently reported measurement of the blazar PKS 0447-439 redshift, with an unexpectedly high value of  $z \geq 1.246$  [1] is of extraordinary importance. TeV gamma rays have

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been detected from PKS 0447-439 [2], but VHE gamma rays cannot traverse distances in excess of 1 Gpc because of inelastic interactions with the extragalactic background light (EBL). If confirmed on a larger sample of TeV blazars, the possibility to observe TeV gamma rays from sources beyond  $z = 1$  will require a dramatic revision of physics and astrophysics of high energy processes in active galactic nuclei, as well as those related to propagation of cosmic rays in intergalactic radiation and magnetic fields. Even for much closer blazars, with redshifts  $z \sim 0.1 - 0.2$ , TeV observations are difficult to reconcile with realistic EBL fluxes [3, 4, 5]. The proposed nonstandard astrophysical explanations invoke very hard intrinsic gamma-ray spectra due to specific shapes of parent electrons [6, 7], or due to internal absorption [8]. More dramatic proposals include violation of Lorentz invariance [9, 10, 11] or “exotic” interactions involving hypothetical axion-like particles [12, 13]. Despite the very different nature of these approaches, their main objective is the same – to avoid severe intergalactic absorption of gamma-rays due to photon-photon pair production at interactions with EBL. This feat was accomplished either by means of big modifications in the cross-sections, or by assuming gamma-ray oscillations during their propagation through the intergalactic magnetic fields (e.g. via photon mixing with an axion-like particle). Alternatively, the apparent transparency of the intergalactic medium to VHE gamma rays can be increased if the observed TeV radiation from blazars is secondary, i.e., if it is formed in the development of electron-photon cascades in the intergalactic medium initiated by primary gamma rays [14]. This assumption can, indeed, help increase the *effective* mean free path of VHE gamma rays, and thus weaken the absorption of gamma rays from nearby blazars, such as Mkn 501 [14, 15]. However, for cosmologically distant objects the effect is almost negligible because the ‘enhanced’ mean free path of gamma rays is still much smaller than the distance to the source. A modification of this scenario can explain TeV signals from objects beyond  $z = 1$  if one assumes that the primary particles initiating the intergalactic cascades are not gamma rays, but protons with energies  $10^{17} - 10^{19}$  eV [16, 17, 18, 19, 20, 21, 22, 23]. The protons can travel cosmological distances and can effectively generate secondary gamma rays along their trajectories. The secondary gamma rays are produced in interactions of protons with 2.7 K cosmic microwave background radiation (CMBR) and with EBL. If IGMFs on cosmological distance scales are smaller than  $10^{-15}$  G, these protons propagate almost rectilinearly, and they carry some significant energy into the last, most important for us segment of their trajectory determined by the condition  $l \leq \lambda_{\gamma,\text{eff}}$ , where  $\lambda_{\gamma,\text{eff}}$  is the *effective* mean free path of gamma rays. The secondary electron-positron pairs produced with an average energy of  $(m_e/m_p)E_p \sim 10^{15}$  eV initiate electromagnetic electron-photon cascades supported by the inverse Compton (IC) scattering of electrons on CMBR and photon-photon pair production of gamma rays interacting with EBL and CMBR. As long as the magnetic field is as small as is required to avoid the smearing of point sources, the cascade develops with an extremely high efficiency. Therefore, the gamma-ray zone is determined by the condition that  $\lambda_{\gamma,\text{eff}}$  be larger (typically, by a factor of 2 or 3) than the gamma-ray absorption mean free-path,  $\lambda_{\gamma\gamma}$  shown in Fig.1.

The efficiency of this scenario depends on the size of the “gamma-ray transparency” zone, and the energy of primary protons. It is approximately determined by the fraction of the proton

energy released in  $e^+e^-$  pairs inside the “gamma-ray transparency” zone, at distances less than  $\lambda_{\gamma,\text{eff}}$  from the observer. Obviously, in the case of a broad energy distribution of protons, the main contribution to the gamma-ray flux comes from some energy range in which the proton mean free path is comparable to the distance to the source:  $d = \lambda_{p\gamma}(E, z = 0)$ . In the case of nearby objects with  $z \ll 1$ , the corresponding energy  $E^*$  can be found from Fig. 1 as the point where the distance to the source is equal the mean free path of protons at the present epoch,  $d = \lambda_{p\gamma}(E^*, z = 0)$ . The contributions of protons with lower or higher energies would be significantly smaller. For lower energies, the interaction probability is too small, while, for higher energies, the energy losses outside the “gamma-ray transparency zone” are too large. However, in the case of cosmologically distant objects, such a simple argument does not work because of very strong dependency of the proton’s mean free path on both the energy and the redshift. It appears that, independent of the initial energy, only the low energy protons with  $E \sim 10^{17}$  eV enter the *gamma-ray transparency zone*. This dramatically reduces the efficiency of production and transport of VHE gamma rays to the observer. At the same time, the efficiencies for gamma rays, the mean free paths of which are comparable to the distance to the source, remain high. This is the case for GeV gamma rays from cosmologically distant,  $z \geq 1$ , objects, and for VHE gamma rays from small- $z$  objects. This can be seen from Fig.2, where we show the SED of gamma rays normalized to the initial energy of the proton. The curves are calculated for two redshifts,  $z = 0.2$  and  $z = 1.3$ , and for several different proton energies.

For gamma rays with energy in excess of several hundred GeV arriving from a source at  $z = 1.3$ , the optical depth is very large,  $\tau_{\gamma\gamma} \sim 10$ , for any realistic model of EBL. VHE gamma-rays cannot survive the severe intergalactic absorption (see Fig. 3), unless one assumes that the reported redshift has a “local” origin, and the source is located much closer to the observer. In order to avoid the catastrophic gamma-ray absorption, in ref. [25] the upper limit on the redshift of the source has been claimed to be smaller than  $z = 0.2$ . However, in this paper we argue that the interpretation of VHE gamma rays as secondary photons, produced in the intergalactic medium at cosmic-ray interactions along the line of sight, does not exclude the location of PKS 0447-439 at  $z = 1.3$ .

Cosmic-ray protons with energy  $E \leq 10^{18}$  eV do not lose a significant part of its energy to interactions with background photons, and, as long as the IGMFs are very weak, the protons can provide an effective transport of the the source’ energy over a large (cosmological) distance toward the observer. Cosmic ray interactions with CMBR and EBL, via the Bethe-Heitler pair production  $p\gamma \rightarrow pe^+e^-$  and the photomeson reactions  $p + \gamma_b \rightarrow p + \pi^0$ , initiate electromagnetic cascades. The secondary VHE gamma rays can be interpreted by an observer as photons arriving from a point source, provided that the broadening of both the proton beam and the cascade electrons due to the deflections in IGMFs does not exceed the point spread function of the detector. In the case of detection of VHE gamma-rays from PKS 0447-439 by the HESS telescope array [2],  $\theta_p, \theta_{\text{cas}} \leq 3$  arcmin. While the broadening of the proton beam takes place over the entire path of protons from the source to the observer (zone 1), the diffusion of electrons in the *transparency zone* (zone 2) is the most important factor for the

broadening of the cascade emission. Therefore, strictly speaking, one should distinguish between the magnetic fields in these two zones,  $B_1$  and  $B_2$ , respectively. The corresponding deflection angles are:  $\theta_p \approx 0.05(E_p/10^{18}\text{eV})^{-1}(B_1/10^{-15}\text{G})\sqrt{(L/1\text{Mpc})(d/1\text{Gpc})}$  arcmin [26] and  $\theta_{\text{cas}} \approx 3.8(E_\gamma/10^{12}\text{eV})^{-1}(B_2/10^{-15}\text{G})$  arcmin, where  $L$  is the coherence length. One can see that, for comparable strengths of magnetic fields in two zones, the angular broadening is mainly due to the electron deflections in the *transparency zone*. Remarkably, such a deflection depends only on the magnetic field  $B_2$  and the gamma-ray energy  $E_\gamma$ . Thus, a detection of an energy-dependent angular broadening of gamma-ray emission from blazars can provide a direct measurements of IGMF in a given direction [27].

The deflections of protons and cascade electrons result in delays of the arrival times of the signal. In the two zones defined above,  $\Delta\tau_p \approx 1.5 \cdot 10^6 (E_p/10^{18})^{-2} (B/10^{-15}\text{G})^2 (L/1\text{Mpc})(d/1\text{Gpc})^2 \text{ s}$  and  $\Delta\tau_\gamma \approx 1.3 \cdot 10^6 (E_\gamma/10^{12} \text{ eV})^{-5/2} (B/10^{-15}\text{G})^2 \text{ s}$ . One can see that, for  $B_1 \sim B_2 \sim 10^{-15} \text{ G}$ , any time structure in the initial signal of  $10^{18}\text{eV}$  protons on time scales of the order of a month or shorter are smeared out. And vice versa, the interpretation of a variable VHE gamma-ray signal on timescales less than 1 month, in the framework of this model, would require magnetic field in both zones to be significantly weaker than  $10^{-15} \text{ G}$ . On the other hand, even for such small magnetic fields, the gamma-ray signals at GeV energies should be stable on timescales of tens of years.

Finally, a distinct feature of the proposed model is the spectral shape of gamma-radiation. For relatively nearby sources,  $z \ll 1$ , the gamma-ray spectrum is flat, with a modest maximum around  $10^{11} \text{ eV}$ . For cosmologically distant sources with  $z \geq 1$ , the spectrum is steep in the sub-TeV part of the spectrum (down to  $10 \text{ GeV}$ ), with a tendency of noticeable hardening above  $1 \text{ TeV}$  (see Fig.2). Remarkably, the spectrum effectively extends to  $10 \text{ TeV}$  and higher energies even for cosmologically distant objects. However, a cutoff in the spectrum below at TeV energies cannot be excluded if the magnetic field in the  $\approx 100 \text{ Mpc}$  vicinity of the observer significantly exceeds  $10^{-15} \text{ G}$ .

For a nearby source, the spectral shape of secondary photons is remarkably independent of the details of the proton energy spectrum [17, 18], although the efficiency decreases dramatically for the proton energy below  $10^{18} \text{ eV}$ . For cosmologically distant sources, the shape of the gamma-ray spectrum does depend on the proton energy, especially at  $E \leq 10^{18} \text{ eV}$ . For a source at  $z \geq 1$ , the proton energy is transferred to gamma rays with a maximal efficiency if  $E \approx 10^{18}\text{eV}$ . Therefore, for an arbitrary spectrum of cosmic rays, the main contribution to secondary gamma rays comes from a relatively narrow energy interval of protons around  $10^{18} \text{ eV}$ . On the other hand, the gamma-ray spectrum produced by these protons in extremely low IGMF ( $B \leq 10^{-17} \text{ G}$ ) disagrees with the broad band SED of gamma rays detected by *Fermi* LAT and HESS as shown in Fig. 3. This suggests the presence of magnetic fields stronger than  $10^{-17} \text{ G}$ . In a stronger magnetic field, deflections of the cascade electrons make the gamma-ray beam at low energies broader. The deflected flux does not contribute to a point source, but rather to the diffuse extragalactic background radiation. Meanwhile, VHE gamma-rays may be confined in the initial narrow beam. This effect is demonstrated in Fig. 3 which is produced using the method described in Ref. [21]. For the IGMF  $B \geq 10^{-17} \text{ G}$ , the GeV gamma-ray flux within an

angle corresponding to the PSF of HESS, drops by two orders of magnitude to the level detected by *Fermi* LAT. The impact on the spectrum of VHE gamma rays is less pronounced, unless the magnetic field exceeds  $10^{-14}$  G.

The results presented in Fig. 3 clearly show that secondary gamma rays can describe correctly the spectrum of PKS 0447-439, as long as IGMFs are in the range  $10^{-17}\text{G} < B < 10^{-14}\text{G}$ , assuming random fields with a correlation length of 1 Mpc. This range of IGMF can be narrowed significantly in the future angular and temporal studies, leading to a more precise measurement of the magnetic field strengths along the line of sight. For example, detection of variability of VHE emission on timescales less than a few days would imply the values of magnetic fields close to  $10^{-17}$  G. It would be also important to search for an unavoidable (in the framework of this model) broadening of the angular extension of gamma-ray signals from cosmologically distant blazars. The choice of the gamma ray energy for such studies depends on the magnetic field. The detection of such an effect would be another strong argument in favor of the proposed scenario, and it would allow an accurate measurements of IGMFs in different directions.

One can see from Fig. 3 that the energy spectrum of gamma rays is quite stable from several hundred GeV to 10 TeV and beyond. Although the current statistics of the results reported by HESS does not allow robust conclusions regarding the energy spectrum above 1 TeV, the detection of multi-TeV gamma rays from PKS 0447-439 as well as from other cosmologically distant blazars would not be a surprise, but rather a natural consequence of the proposed scenario. However, we note that if the magnetic field is enhanced in the *transparency zone*, i.e. in the vicinity of the observer, it could cause strong suppression of the gamma-ray flux above some energy which can be found from the condition of  $\lambda_{\gamma\gamma}(E) = D$ . The impact of this effect on the gamma-ray spectrum detected by an observer, strongly depends on the linear scale of the enhanced magnetic field,  $D$ , but not much on the magnetic field itself (as long as the latter is significantly larger than  $10^{-15}\text{G}$ ). For example, for  $D \sim 300$  Mpc, the steepening of the gamma-ray spectrum starts effectively around 1 TeV. This effect is illustrated qualitatively in Fig. 3.

The isotropic luminosity of the source in protons required to explain the data [2], is in the range  $(1-3) \times 10^{50}$  erg/s, depending on the spectrum of protons. This is an enormous, but not an unreasonable power, given that the actual (intrinsic) luminosity can be smaller by several orders of magnitude if the protons are emitted in a small angle. In particular, for  $\Theta = 3^\circ$ , the intrinsic luminosity is comparable to the Eddington luminosity of a black hole with a mass  $M \sim 10^9 M_\odot$ . Assuming that only a fraction of the blazar jet energy is transferred to high-energy particles, the jet must operate at a super-Eddington luminosity. While it may seem extreme, this suggestion does not contradict the first principles of accretion, provided that most of the accretion energy is converted to the kinetic energy of an outflow/jet, rather than to thermal radiation of the accretion flow. Moreover, there is a growing evidence of super-Eddington luminosities characterizing relativistic outflows in GRBs and in very powerful blazars [29].

Finally, we note that the protons emitted by cosmologically distant objects are potential contributors to the diffuse gamma-ray background. The total energy deposited into the cascades

through secondary Bethe-Heitler pair production does not depend on the orientation of the jet or the beaming angle, but only on the injection power of  $\geq 10^{18}$  eV protons and on the number of such objects in the universe. Generally, the total energy flux of gamma rays is fairly independent of the strength of the intergalactic magnetic fields, except for the highest energy part of the gamma-ray spectrum. If the contribution of these sources to the diffuse gamma-ray background is dominated by cosmologically distant objects, then the development of the proton-induced electron-photon cascades is saturated at large redshifts. One should, therefore, expect a rather steep (strongly attenuated) spectrum of diffuse gamma rays above 100 GeV. However, in the case of very small intergalactic magnetic fields, the  $10^{18}$  eV protons can bring significant amount of non-thermal energy to the nearby universe, and thus enhance the diffuse background by TeV photons. Perhaps, this can explain the unexpected excess of VHE photons in the spectrum of the diffuse gamma-ray background as revealed recently by the *Fermi* LAT data [30].

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## References and Notes

- [1] H. Landt, *MNRAS*, **423**, L84 (2012).
- [2] A. Zech, *et al.* (HESS collaboration), *PoS TEXAS2010*, 200 (2010).
- [3] F. Aharonian, *et al.*, *Nature* **440**, 1018 (2006).
- [4] A. Franceschini, G. Rodighiero, M. Vaccari, *Astron. Astrophys.* **487**, 837 (2008).
- [5] R. Gilmore, R. Somerville, J.R. Primack, A. Dominguez, *MNRAS*, **422**, 3189 (2012).
- [6] F. Tavecchio, G. Ghisellini, G. Ghirlanda, L. Costamante, A. Franceschini, A., *MNRAS*, **399**, L59 (2009).
- [7] E. Lefa, F. Rieger, F. Aharonian, *Astrophys.J.* **740**, 64 (2011).
- [8] O. Zacharopoulou, D. Khangulyan, F.A. Aharonian, L. Costamante, *Astrophys.J.* **738**, 157 (2011).
- [9] T. Kifune, *Astrophys. J.* **518**, L21 (1999)
- [10] F.W. Stecker, S.L. Glashow, *Astroparticle Physics*, **16**, 97 (2001)
- [11] U. Jacob, T. Piran, *Physical Review D*, **78**, id. 124010 (2208)
- [12] A. De Angelis, O. Mansutti, M. Roncadelli, *Phys.Rev.* **D76**, 121301 (2007).
- [13] M. Simet, D. Hooper, P. D. Serpico, *Phys.Rev.* **D77**, 063001 (2008).
- [14] F.A. Aharonian, A.N. Timokhin, A.V. Plyasheshnikov, *Astron. Astrophys.* **384**, 834 (2002).

- [15] A. Taylor, I. Vovk, A. Neronov, *Astron. Astrophys.* **529**, 144 (2011).
- [16] W. Essey, A. Kusenko, *Astropart. Phys.* **33**, 81 (2010).
- [17] W. Essey, O. E. Kalashev, A. Kusenko, J. F. Beacom, *Phys. Rev. Lett.* **104**, 141102 (2010).
- [18] W. Essey, O. Kalashev, A. Kusenko, J. F. Beacom, *Astrophys. J.* **731**, 51 (2011).
- [19] K. Murase, C. D. Dermer, H. Takami, G. Migliori, *Astrophys. J.* **749**, 63 (2012).
- [20] S. Razzaque, C. D. Dermer, J. D. Finke, *Astrophys. J.* **745**, 196 (2012).
- [21] W. Essey, S. Ando, A. Kusenko, *Astropart. Phys.* **35**, 135 (2011).
- [22] W. Essey, A. Kusenko, *Astrophys. J.* **751**, L11 (2012).
- [23] A. Prosekin, W. Essey, A. Kusenko, F. Aharonian, *arXiv:1203.3787* (2012).
- [24] A. Prosekin, S. Kelner, F. Aharonian, *Astron. Astrophys.* **536**, A30 (2011).
- [25] E. Prandini, G. Bonnoli, F. Tavecchio, *arXiv:1110.4038* (2011).
- [26] F.A. Aharonian, S. R. Kelner, A. Prosekin, *Phys. Rev. D.* **82**, 043002 (2010).
- [27] S. Ando, A. Kusenko, *Astrophys. J.* **722**, L39 (2010).
- [28] A. A. Abdo, *et al.*, *Astrophys. J.*, **700**, 597 (2009).
- [29] G. Ghisellini, 25th TEXAS Symposium on relativistic atrophysics, AIP Conference Proceedings **381**, 180 (2011).
- [30] K. Murase, J.F. Beacom, H. Takami, *arXiv:1205.5755* (2012).

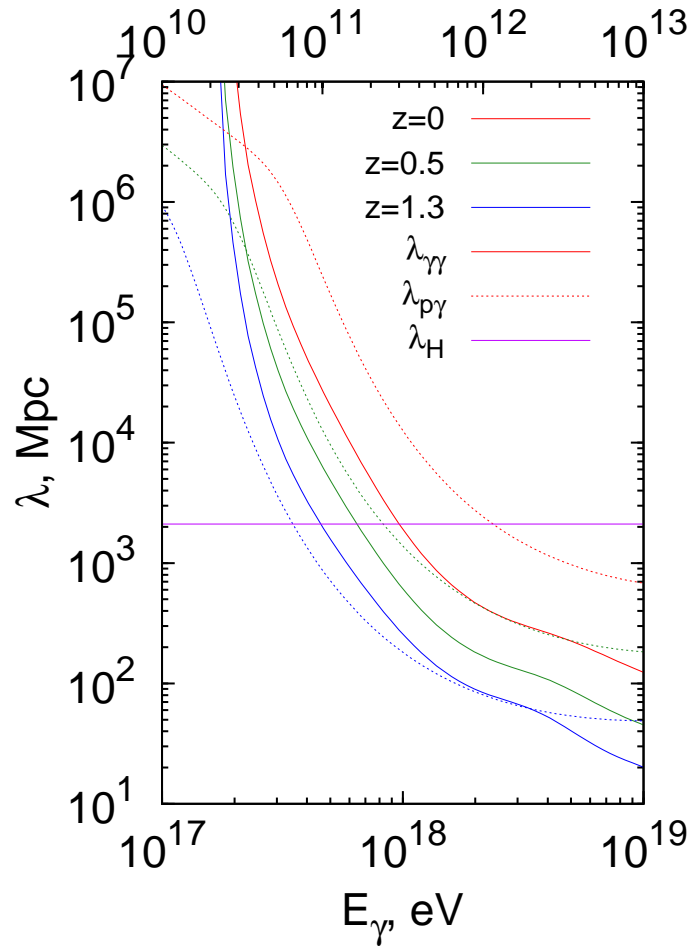


Figure 1: The mean free path of protons as a function of energy and the source redshift. The calculations are based on the formalism developed in Ref. [24]. The gamma-ray absorption mean free path  $\lambda_{\gamma\gamma}$  corresponding to the model of Ref. [4] is also shown.



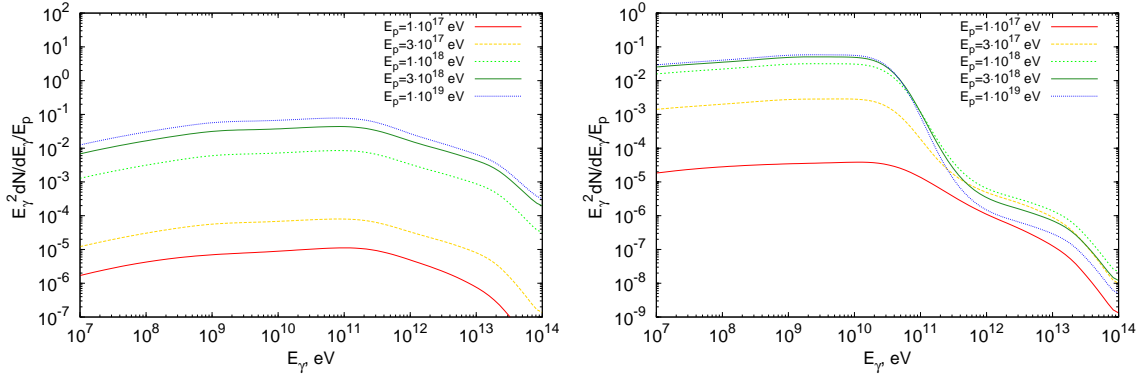


Figure 2: The energy spectra of secondary gamma rays produced by protons of different energies emitted from a source at  $z = 0.2$  (left panel) and  $z = 1.3$  (right panel). The curves are normalized to the proton energy, hence, they show the differential efficiency of the energy transfer from protons to gamma rays. It is assumed that the intergalactic magnetic field  $B = 0$ .

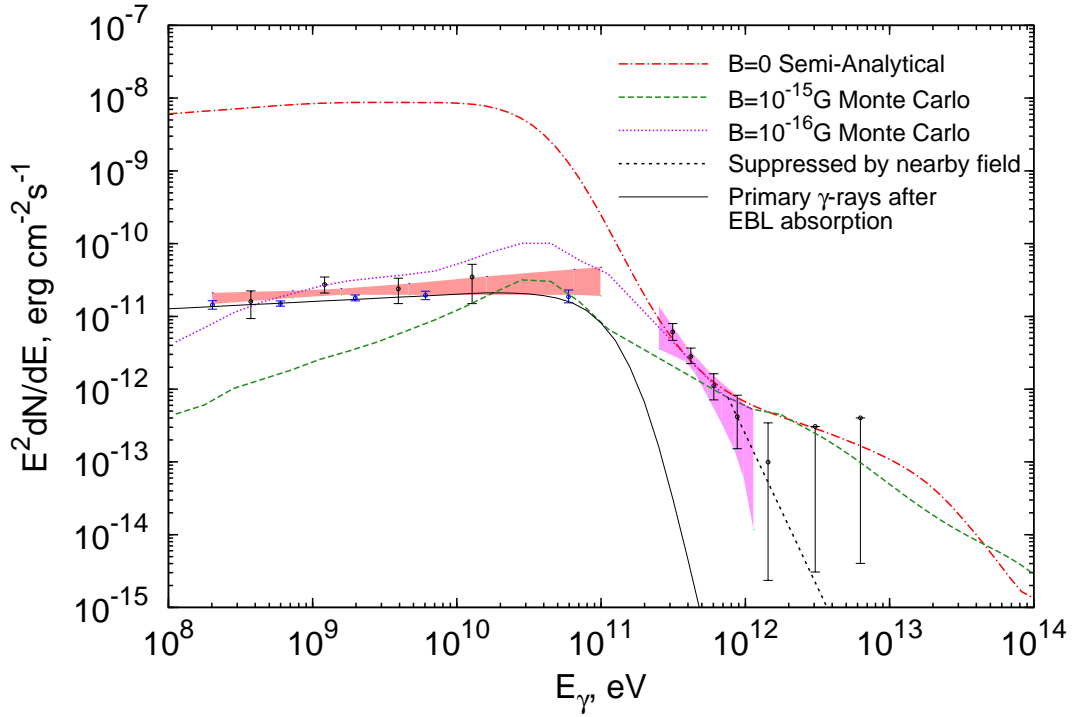


Figure 3: Spectra of secondary gamma rays produced by protons, calculated using semi-analytical and Monte Carlo techniques. All theoretical curves are normalized to the observed flux around 1 TeV. The data points are from *Fermi* LAT [28] and HESS [2]. The semi-analytical calculations correspond to the magnetic field  $B = 0$  and protons injected with  $E_p^{-2}$  type energy spectrum in the energy interval  $E_p = 10^{17} - 10^{18}$  eV. Monte Carlo results for the secondary spectrum from protons with a high energy cutoff of  $10^{19}$  eV are shown for IGMF  $B = 10^{-16}$  G and  $B = 10^{-15}$  G. The effect of significantly enhanced magnetic field within  $D \lesssim 300$  Mpc around the source is shown for illustration of a possible suppression of the spectrum above 1 TeV. Also shown is the spectrum from a pure-gamma (no cosmic rays) source with injection spectrum  $E_\gamma^{-2}$ , after intergalactic absorption for EBL model of Ref. [4].